APPENDIX F
ESTIMATING THE EXTENT OF THE OLIGOHALINE ZONE IN THE NORTH FORK OF THE ST. LUCIE RIVER AND ESTUARY UNDER LOW FLOW CONDITIONS

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SUMMARY

The location of the 5-parts per thousand (ppt) isohaline zone in the North Fork of the St. Lucie River and Estuary under steady state conditions is estimated using two methods: a one-dimensional analytical solution and a two-dimensional hydrodynamic Research Management Associates, Inc., (RMA) model. The 5-ppt isohaline zone is traditionally considered to be the transition between the saltier mesohaline and the fresher oligohaline habitats. Its location is used here to define the downstream extent of viable oligohaline habitat under low flow situations. The one-dimensional analytic method is calibrated using salinity data collected at the Kellstadt Bridge (FOS station 1), and flow data collected at the Gordy Road Structure during 1999 and 2000. Hu calibrated the two-dimensional RMA model at the Roosevelt Bridge located in the St. Lucie Estuary. This calibration is discussed in **Appendix H**. A logarithmic relationship is developed relating the salt intrusion position to the discharge rate. The relationship is similar for both solution methods. This relationship can be used to estimate the extent of the viable oligohaline zone in the riverine portions of the North Fork.

BACKGROUND

This work is conducted as part of the Indian River Lagoon Restoration Feasibility Study (USACE and SFWMD, 2001) and also as part of the effort to establish minimum flow and levels (MFLs) for the St. Lucie Estuary. Protection of a viable oligohaline habitat depends in part on the maintenance of sufficient flows within the riverine reaches of the St. Lucie River watershed. Since most of the riverine portions of the watershed are in the historic North Fork, this paper is limited to North Fork modeling. Previous hydrodynamic modeling (**Appendix H**) within the St. Lucie Estuary focused on periods of moderate to high runoff when the riverine portions of the estuary were fresh. For this reason, previous modeling did not extend into the riverine portions of the estuary.

Minimum flow conditions are associated with droughts and periods of low rainfall. Under low flow conditions, salinity throughout the estuary increases and the oligohaline area is reduced as higher salinity destroys or displaces oligohaline flora and fauna. This MFL work is directed at estimating the extent of the oligohaline under various low flow conditions. Since flows are relatively stable during low flow periods it is assumed that steady state solutions can adequately predict salinity within the upstream reaches.

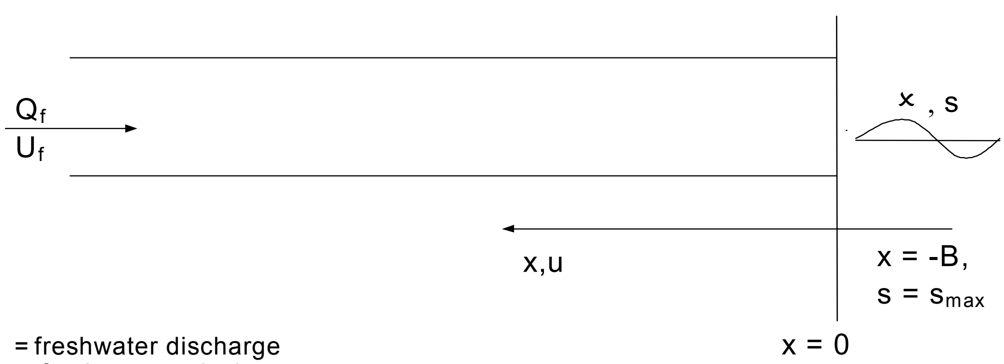
This appendix describes two steady state methods for predicting the location of the 5-ppt isohaline zone. The calibration of the analytical method is also described. The methods are applied to two minimum flow situations (the end of a 1-in-10 year drought). One MFL situation is North Fork flows under predeveloped (Natural System Model [NSM]) conditions. The other situation is flow from today's watershed (1995 Base Case) under the same low rainfall conditions. The equivalent flow-location relationships exist for both the 1995 Base Case and NSM conditions using either the analytical or RMS method. The resulting simple flow-location relationship is being applied elsewhere in the continued development of MFL criteria.

ONE-DIMENSIONAL ANALYTICAL SOLUTION

Basic Equations

The objective of the one-dimensional analytical solution is to calculate the location of the isohaline zone in a tidal driven channel with freshwater discharge. The isohaline zone will have 5-ppt or 10-ppt salinity. The method described below in **Figure F-1** and the equations came from Ippen (1966).

At x = 0, ocean end; at t = 0, it is low tide



Q_f = freshwater discharge
U_f = freshwater velocity
s_{max} = the maximum salinity at the tidal boundary
B = the distance from tidal boundary to ocean where salinity reaches s_{max} at low tide

Figure F-1. Sketch of salinity intrusion in tidal influenced channel at low tide

Equations 1 and 2 are the basic equations of the one-dimensional analytical solution:

$$\frac{\partial s}{\partial t} + u\frac{\partial s}{\partial x} = \frac{\partial}{\partial x}\left(D_x \frac{\partial s}{\partial x}\right) \quad (1)$$

At any point, the flow velocity in the channel is equal to the sum of the velocity due to tidal motion u(x,t) and the freshwater velocity $-U_f$, thus

$$\frac{\partial s}{\partial t} + u(x,t)\frac{\partial s}{\partial x} - U_f \frac{\partial s}{\partial x} = \frac{\partial}{\partial x}\left(D_x \frac{\partial s}{\partial x} \right) \tag{2}$$

Where $D_x(x,t)$ is the diffusion coefficient.

Solution

Salinity Distribution at Low Tide

The salinity distribution at low tide is determined using Equation 3.

$$\ln \bar{s} + C_2 = -U_f \int \frac{dx}{D_x} \tag{3}$$

Diffusion without Density Difference

The diffusion coefficient can be stated as follows:

$$D_x = 14.2hu\frac{\sqrt{2g}}{C_c} = 7.1hu\sqrt{f}\,, \quad C_c = \sqrt{8g/f} \tag{4}$$

The average value of D_x in a tidal cycle linearly depends on u, which is computed from tidal propagation and decreases with x in an upstream direction. For uniform cross-sections, a simplest functional relationship can be used:

$$D_x = \frac{D_0 B}{x + B} \tag{5}$$

Therefore,

$$\ln \frac{c}{c_0} = -\frac{U_f}{2BD_0}(x + B)^2 \tag{6}$$

at x=-B, c= c_0.

Diffusion with Density Difference

The diffusion with density difference is calculated using Equation 7:

$$\ln \frac{s}{s_{\max}} = -\frac{U_f}{2BD_0^{'}}(x_l + B)^2 \qquad \text{for } (x_l + B) > 0 \tag{7}$$

The minimum salinity intrusion length at low tide:

$$L_m = x_l = B\left(\sqrt{-\frac{2D_0^{'}}{U_f B}\ln \frac{s}{s_{\max}}} - 1\right) \tag{8}$$

The maximum salinity intrusion length at high tide is in the range of L_m and L_m+B.

Determine B and D_0'

The distance from the tidal boundary to the ocean where salinity reaches s_{max} at low tide (B) is determined using Equation 9:

$$B = \frac{u_{\max}}{\sigma}(1 - \cos \sigma t_B) \tag{9}$$

The diffusion coefficient (D_0') is calculated using Equation 10. Because the salinity is in the range of 5 to 15 ppt, assume $D_0' = D_0$

$$D_0^{'} \sim hu_{\max}\frac{\sqrt{2g}}{C_c}, \quad C_c = \frac{1}{n}R^{1/6}, \quad R = \frac{bh}{b + 2h} \tag{10}$$

Where t_B is the time the salinity at the entrance reaches the maximum value s_{max} and s_{max} is the maximum salinity at low tide at x_l = 0. The final D_0' is obtained from calibration. t_B and s_{max} can be identified from the salinity profile at the ocean end.

Input Parameters

The input parameters for the one-dimensional analytical solution are provided in **Table F-1**.

Table F-1. Input Parameters

Symbol	Parameters	Sources
b	Width	Cross-section profile
h	Depth	Cross-section profile
n	Manning coefficient	
u_{max}	Maximum velocity at the tidal end boundary	Tidal boundary
s	Tidal frequency	Tidal boundary
U_f	Freshwater velocity	Fresh water discharge Q_f and river cross-section area A
s_{max}	Maximum salinity at tidal end boundary	Salinity series at tidal boundary
t_B	Time the salinity at the entrance reaches the maximum value s_{max}	Salinity series at tidal boundary

Implementation Procedures

- Determine σ, u_{max}, and s_{max} from the tidal boundary condition
- Determine river depth h and calculate $U_f = Q/A$, where Q is the freshwater discharge rate at cubic meters per second and A is the cross-section area of the river
- Determine t_B and s_{max} with the salinity series boundary condition
- Calculate B and D_0' from Equations 9 and 10
- Calculate minimum salinity intrusion at low tide with equation (8)

Calibration

The calibration data set is composed of three parts: Florida Oceanographic Society (FOS) Station 1 salinity data (**Figure F-1**), Gordy Road Structure flow data, and Kellstadt Bridge salinity and current data maintained by the United States Geological Survey (USGS).

Salinity data from FOS Station 1 was taken by volunteers every week since 1998. Station 1 is located 1 mile north of the Prima Vista Bridge (section N044) and 4 to 5 miles north of the Kellstadt Bridge (section N067) (Longitude 80° 19.887' W, Latitude 27° 19.724' N).

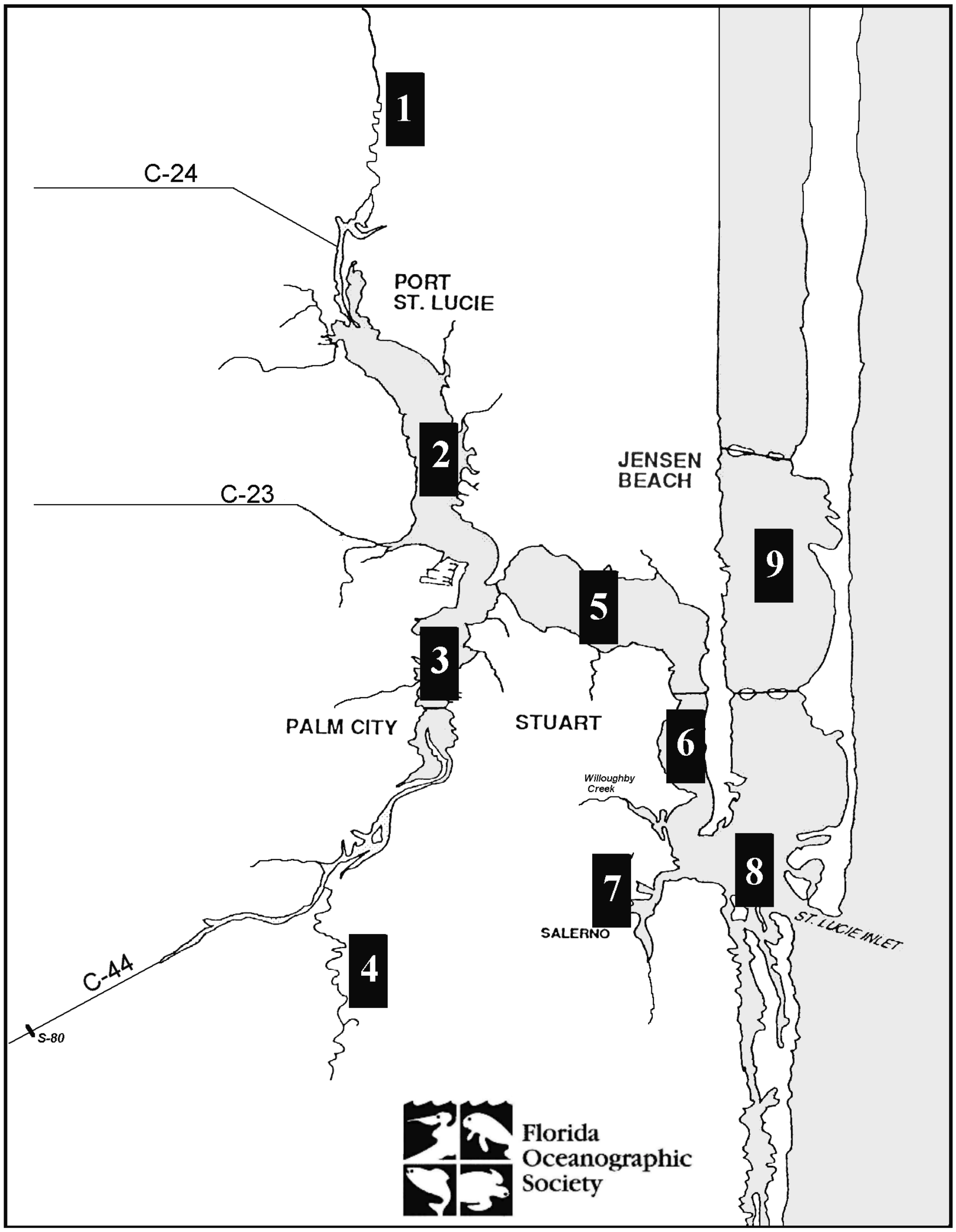


Figure F-2. Florida Oceanographic Society Monitoring Stations

The Kellstadt Bridge station was monitored by USGS until 2000. The monitoring data collected includes water surface elevation, current, and salinity at the top and bottom layers.

The discharge rate at the Gordy Road Structure on Ten Mile Creek has been monitored since 1999. The discharge rate on the North Fork is estimated based on drainage area (**Table F-2**). The approximation in North Fork discharge estimation is probably one of the greatest error terms in this simulation.

Table F-2. North Fork Discharge Derived from Gordy Road Structure Discharge

Drainage Basins	Drainage Area (Acres)
Ten Mile Creek	29,380
Five Mile Creek	7,000
North Fork - Total	105,613
North Fork - uncontrolled area flowing into North Fork	63333
$Q_{NF} = Q_{TMC} * (1 + 63{,}333/29{,}380) = Q_{TMC} * 3.16$ Q_{NF} is the total discharge on the North Fork and Q_{TMC} is the discharge on Ten Mile Creek measured at the Gordy Road Structure	

Based on 22 cross-section profiles, it was determined that the North Fork is deeper and wider (230 feet) and meanders down from the Prima Vista Bridge (N035-N072). From Prima Vista Bridge to the upper reach (N01-N035), the river is narrower (85 feet) and shallower. During calibration, the width is fixed constant to 6.5 feet between FOS Station 1 and Kellstadt Bridge. Three calibration scenarios were selected based on the comparison of overlap periods among these 3 data sets (**Table F-3**).

Table F-3. Calibration Scenarios

Calibration scenarios	**March 19, 2000**	**January 23, 2000**	**December 19, 1999**
Freshwater discharge (Q_f) (cubic feet per second)	90	180	260.9
Kellstadt Bridge salinity (ppt)	12	8	3
Salinity at FOS station 1 (north of Prima Vista Bridge) (ppt)	4	2	1.2
Maximum Tidal velocity (u_{max}) (meters per second)	0.3	0.3	0.2
Maximum salinity at tidal end (ppt)	14.8	10.2	5
Minimum salinity at tidal end (ppt)	11	5	1.5
Width (d) (feet)	230		
Depth (h) (feet)	6.5		
Length (mile)	6.4		
Manning coefficient	0.04		
t_B	0.45 Tidal Period		

The diffusion coefficient is crucial for salinity intrusion due to tidal mixing and density gradient. The density gradient effect is reflected in freshwater discharges and salinity at the tidal end. To account for this, the diffusion coefficient is adjusted with a correction factor in the prediction:

$$D_0^{'} = D_0 \cdot f(Q_f) \cdot f(\frac{s_{\max}}{s_{\min}}) = D_0 \cdot \frac{Q_f\,(calibration\ base)}{Q_f} \cdot \frac{\ln(\frac{s_{\max}}{s_{\min}})(calibration\ base)}{\ln(\frac{s_{\max}}{s_{\min}})} \qquad (11)$$

Analytical solution is limited with uniform sections. Therefore, average depth is adjusted to 5 feet at low flow conditions based on the two-dimensional simulation results, which is described in the next section.

With the progress of the tide into the river, the velocity amplitude is damped exponentially. In addition, the celerity of wave is reduced by a factor related to wave length. This factor is 0.71 to 0.94 (Ippen, 1966). A conservative correction factor of 0.9 is used.

The one-dimensional analytical solution is limited with simplifications. Through the calibration and prediction process, river depth, river width, maximum salinity, and velocity at the tidal boundary are identified as sensitivity parameters. River depth and width are simplified as uniform. The measured velocity at the Kellstadt Bridge by the USGS is used in the prediction. In addition, the diffusion coefficient is assumed linearly decreased with the propagation of tide. All these approximations introduce uncertainty into the prediction and reflect the limitation of the method.

TWO-DIMENSIONAL SIMULATION ON EXTENDED ESTUARY GRIDS WITH THE RMA MODEL

The RMA finite element grid was extended from Kellstadt Bridge to the Gordy Road Structure. The new grid is shown in **Figure F-3**. The two-dimensional RMA model is calibrated around the Roosevelt Bridge in the St. Lucie Estuary by Hu (**Appendix H**). Due to time limitations, it was not further calibrated for the North Fork.

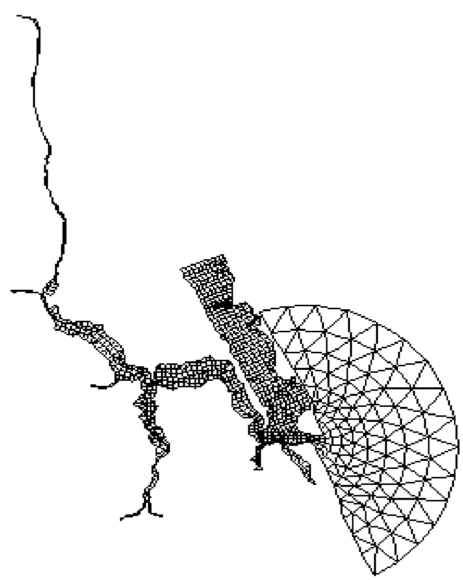


Figure F-3. Two-Dimensional Simulation Grid for the North Fork and the St. Lucie Estuary

RESULTS

Prediction scenarios were selected for 1995 Base Case and NSM model simulations based on the time periods when discharge is relatively stable. Five scenarios were selected for the 1995 Base Case simulations (**Table F-4** and **Figure F-4)** and four were selected for the NSM simulations (**Table F-5** and **Figure F-5**).

Table F-4. Prediction Scenarios for the 1995 Base Case

Julian Day	27-42	95-105	19-24	74-79	112-117
Q_f (cfs)	235	130	80	35	25
s_{max}		9.5	13	15	18
s_{min}		6	9	10.5	13
s_{avg}	3.8	8.5	11	12.5	15
L_{avg} (mile)	0	3.4	5.5	7.5	12.6
% of NF length	0	0.14	0.22	0.3	0.5
L_{avg} compared to RMA4 result	0	5.3	4.0	6.0	8.2
% of NF length	0	0.21	0.16	0.24	0.33

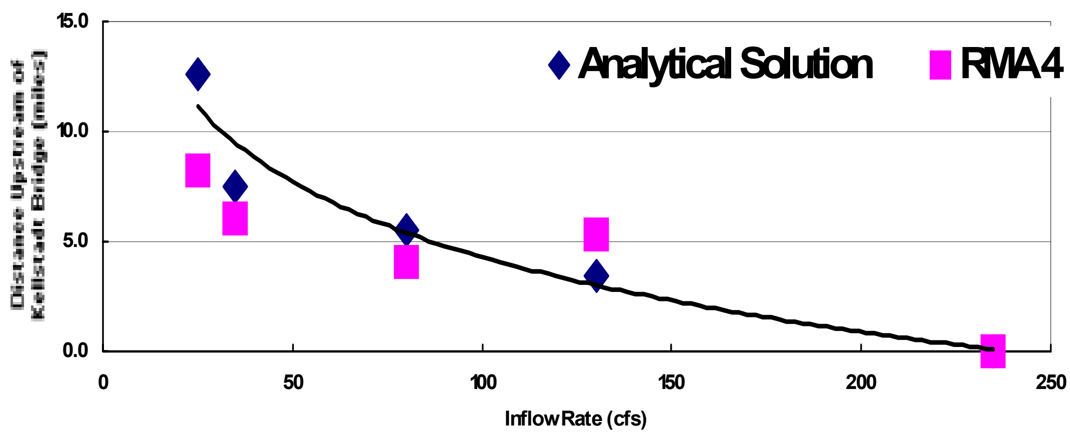


Figure F-4. Location of the 5-ppt Isohaline Zone for the 1995 Base Case Simulations

Table F-5. Prediction Scenarios for the NSM Simulations

Julian Day	112-119	10-30	52-60	34-50
Q_f (cfs)	20	80	100	120
s_{max}	17.5	14	14	10
s_{min}	14	9	8	6.5
s_{avg}	16	11	10	8
L_{avg} (mile)	13.4	5.5	4.2	3.2
% of NF length	0.54	0.22	0.17	0.13
L_{avg} compared to RMA4 result	10.9	5.7	3.4	2.1
% of NF length	0.43	0.23	0.14	0.08

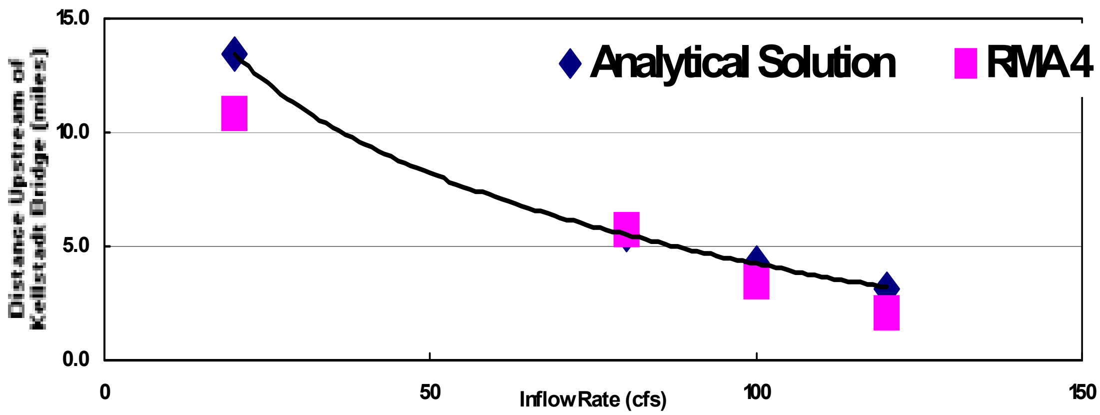


Figure F-5. Location of the 5-ppt Isohaline Zone for the NSM Simulations

Based on the results from the two methods, the location of 5-ppt isohaline zone and discharge rate has these relationships:

$L = -4.9 \ln(Q_f)+27$ for the 1995 Base Case

$L = -5.7 \ln(Q_f)+30.5$ for the NSM

When discharge is larger than 230 cfs for the 1995 Base Case, the 5-ppt isohaline zone is past the Kellstadt Bridge on the North Fork.

CONCLUSION

Predictions of the location of the isohaline zone on the North Fork is conducted with simplifications for a quick solution. Compared with Kellstadt Bridge salinity data from USGS, it is concluded that RMA results underestimated the salt intrusion length on the North Fork, while the one-dimensional analytical solution result is limited by too many simplifications. Due to the limitation of time, the accuracy of the result is compromised.

This simulation will be applied to the determination of the oligohaline zone on the North Fork under minimum flow condition for three scenarios: 1995 Base Case, NSM, and 2050.

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